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Advances in Experimental Exposure Methods and Dosimetric Techniques Used in Radio-Frequency Radiation Biological Effects Studies

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Abstract—The various techniques and methodologies used for exposure and dosimetric assessment in radio-frequency (RF) biological effects studies are reviewed. Techniques are compared and the advantages and disadvantages of each are discussed. Significant progress has been made during the past decade in developing the specialized techniques required; suggestions are given for further studies.

I. Introduction

DURING the past decade, the continuing controversy surrounding the biological effects and possible health hazards of radio-frequency (RF) electromagnetic (EM) radiation [1] has fostered much interest in and support for experimental research. All of these experimental efforts involve whole- or partial-body exposures of experimental animals as well as various *in vitro* preparations, cellular suspensions, etc. This paper reviews the significant advances made during this period in developing the specialized exposure methods and dosimetric assessment techniques needed for such research, and discusses the inherent advantages and disadvantages of each. To limit the scope, emphasis is placed on experimental techniques associated with whole-body irradiation of animals.

The first part of this review discusses exposure methods, including techniques of holding animals during exposure as well as methods of providing food and drinking water during exposure. The second deals with dosimetric techniques for determining the average whole-body and localized specific absorption rate (SAR), a quantity defined as the mass-normalized rate of energy absorbed by an irradiated subject.

To conserve space, illustrations are not included in this review. The reader is referred to the original papers for the illustrated details of the topic under consideration.

II. Exposure Methods

A diversity of exposure methods is available to researchers. Their choice depends on the specialized application involved, the existing facilities available for experimentation, and the cost of setting up new facilities. The choice of exposure system is important since the system chosen can affect the outcome of an experiment. Under some circumstances, one type of exposure system can optimize the biological response that is under study, whereas with another type, the effect may no longer be detectable. These problems clearly emphasize the need for both engineer and biologist, to work together to develop experimental protocols in a multidisciplinary approach to this complex research area.

This diversity has tended to create difficulties in reproducing biological effects data, and may have further fueled controversies surrounding the existence of some reported effects. Whereas, an effect may have been noted by one group of researchers who employed a particular exposure system, a second group, who carefully attempted to reproduce the experiment in every detail but for the exposure method, frequently would be unable to observe the reported effects. It is possible that basic differences in the exposure environment may, in some cases, explain this lack of reproducibility.

Because of these factors, it must be concluded that the various methods of exposure are unique; results obtained from different exposure environments generally cannot be compared except on a whole-body-averaged SAR basis, and reproducibility of experimental data is not guaranteed unless identical methodology is used.

Many of the specialized requirements of a particular experiment are unique. However, there are some requirements that are common to almost all experiments. For example, there is a critical need to regulate temperature and humidity in the environment in which animals, biological test samples, etc., are located. This precaution ensures that the ambient air temperature and humidity are properly controlled, thereby minimizing the possibility of unwanted variables in the experimental protocol. Two other requirements are common to most experiments involving whole-body irradiation of animals: a) the biologist's need to expose a sample of animals that is large enough to allow for statistically reliable conclusions to be drawn, and b) a similar need for an equally large sample of control animals that must be housed during the exposure periods under conditions that are in every way identical to those of the irradiates except for the presence of RF energy. Many of the early experimental RF biological effects studies frequently contained no provisions for controls, involved inadequate numbers of experimental subjects, and lacked adequate provisions for environmental control, thus making the validity of their results questionable. It is only within the past decade that researchers have succeeded in correcting most of these protocol deficiencies.

Methods of exposing animals to RF radiation cannot be adequately addressed without a brief initial discussion of how biological objects interact with RF EM fields. While it is beyond the scope of this paper to delve into this subject a few important points will be summarized here. The absorption of RF energy in an exposed object depends principally on 1) the object size in relation to the RF radiation wavelength, 2) the

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orientation of the object in relation to the electric field (E-field) vector (i.e., the EM wave polarization), and 3) the complexity of the incident radiation (i.e., whether the EM wave is propagating or standing, plus its wave-impedance value). Much effort has been expended, both predictive and experimental, on characterizing the RF absorption properties of various biological objects under differing exposure conditions. These data have been collected together in the *RF Dosimetry Handbook* [2]. In these studies, RF absorption is shown to reach a peak in a certain frequency range, given a particular object orientation. This is the resonant absorption condition and represents an optimal exposure condition that experimenters frequently strive for due to the high efficiency of RF energy coupling into an object. Exposures involving frequencies that are below or above the resonant absorption range are usually termed "subresonant" and "superresonant" exposures, respectively. In the subresonant region (also termed a "long-wavelength" exposure) the RF absorption is much lower than in the resonant range, but the energy deposited in the exposed object is uniformly distributed. This is not the case for the resonant and superresonant regions where the energy deposited is nonuniformly distributed, giving rise to so-called "hot-spot" regions.

Commonly used exposure methods can be categorized into two basic groups, namely, free-field or enclosed.

A. Free-Field Systems

Historically, free-field exposure methods were the first to be used in biological effects experimentation, and still remain the most commonly used techniques. These methods involve placing the experimental subjects(s) in the far field of a radiating antenna, such as a horn or parabolic dish. To establish accurately the power-density levels at the subject's location, all unwanted scattering of RF energy from the surrounding room structure, etc., must be minimized to the greatest extent possible. This constraint requires using a microwave-absorbing material that wholly or partially surrounds the experimental subjects, creating what is termed an "anechoic chamber." (The term "anechoic," meaning "without echoes," is borrowed from acoustics research.) The design of anechoic chambers is a highly specialized art usually performed by commercial manufacturers of absorbing materials. The RF performance of such chambers, which is defined by the characteristics of the "quiet zone" where the subjects are placed, is a function of the reflectivity properties of the absorbing material with which the chamber is lined. Reflectivity refers to the degree with which RF energy is reflected, rather than absorbed, by the materials. The reflectivity of the anechoic material is proportional to the incident wavelength so that the performance of an anechoic chamber markedly deteriorates as the frequency of operation is lowered. A minimum reflectivity of 20 dB (0.01) is usually considered essential; the frequency at which this value is reached then defines the lower frequency limit of operation for the chamber. Generally, anechoic chambers perform very well at frequencies in the microwave region of the spectrum (above ~500 MHz). However, satisfactory performance at lower frequencies or longer wavelengths requires using large blocks of absorbing material that contain long pyramids or cones. Building a structure large enough to house such a chamber involves costs that render it impractical. For all intents and purposes, it is not feasible to consider construction of anechoic facilities that operate at frequencies under ~250 MHz.

Today, extensive anechoic chamber facilities devoted to RF biological effects work can be found at government, university, and industrial research laboratories throughout North America and Europe. These vary considerably in size and sophistication; some [3] contain provisions for highly accurate control of ambient temperature and humidity, while others have little or no such capability. In some cases, the experimental subjects are irradiated from the ceiling while in others the RF energy is horizontally directed.

The principal advantages of the free-field exposure method are as follows:

1) The unperturbed incident power density to which the subject is exposed can be well defined within an accuracy of ±1 dB (±20 percent) or less. Replication of experiments performed under free-field conditions is, therefore, relatively straightforward.

2) Depending on the directionality of the radiating antenna, the exposure area where irradiated subjects are placed is relatively large and the field distribution is generally uniform (±10 percent or less).

The principal disadvantages of free-field exposure methods are as follows:

1) The facilities are costly and often require extensive floor space.

2) High-power RF sources are needed to obtain the necessary power-density levels. As a result, many free-field facilities employed in biological effects research operate on either of two industrial, scientific, and medical (ISM) frequency assignments used for microwave heating, 2450 or 915 MHz, where high-power sources are commercially available at relatively low cost. This is why 2450 MHz has become a standard RF frequency in biological effects research.

3) Free-field systems are an excellent simulation of the idealized exposure concept visualized in existing protection standards involving a plane-wave unipath exposure, but are not representative of the real-world exposure situations encountered by humans, which usually involve much more complex fields.

4) The whole-body SAR cannot be measured directly in a free-field situation. However, reasonably accurate estimates of the SAR can be made by calorimetric measurements of irradiated animal carcasses or by numerical calculations.

Various attempts have been made to modify conventional free-field exposure methods to ameliorate the associated cost and space problems. Workers at the Georgia Institute of Technology developed several techniques [4]. One of these, the absorber-lined horn antenna, enables a subject to be placed much closer to the horn aperture and yet still be within the far-field zone of the radiator than is the case with a conventional horn. This placement means that a lower power source can be used to create the same power density. Another technique is the compact-range system that uses a feed horn to illuminate a large parabolic reflector. The test subject is exposed in the collimated-ray region of the reflector. The advantage of this system is that it creates a much larger test volume of relatively uniform field intensity with an associated reduction in the overall size of the anechoic facility as well as reduced requirements for absorbing materials.

As mentioned earlier, an important criterion in whole-body exposure of animals is the need to expose large numbers of animals. Consequently, in many experiments unrestrained animals are frequently placed together in a closely spaced matrix inside an anechoic chamber and exposed simultaneously.

This practice tends to obviate the principal advantage of free-field exposure methods because it is no longer possible to define accurately the power density to which the animals are exposed owing to RF energy scatter from one animal to another. The degree of scatter is dependent on much the same factors as absorption [2] and is most serious when the frequency of exposure lies in the resonant and superresonant regions. Large changes in scattered energy are created by possible changes in the relative posture and orientation of the animals. Various solutions have been devised including the following:

1) sequential exposure of single animals in the same free-field facility;
2) use of miniature anechoic chambers to expose animals individually;
3) separating out restrained animals so that they are spaced by a minimum of one wavelength.

The first solution is obviously costly and time consuming and may not be acceptable in certain critical biological experiments that require all animals to be exposed at exactly the same age and/or the same time of day, etc. The second solution was advanced by Guy [5] who describes a system of 16 miniature anechoic chambers designed for chronic low-level (<10-mW/cm^2) exposure of rabbits and rodents at 2450 MHz. Eight of these chambers are energized while the rest house controls. The obvious advantages are that total RF isolation between animals is ensured, and cost and RF power requirements may be lower than for a conventional large-scale anechoic facility.

The third solution was tried by a few workers and appears to be a reasonable compromise between the conflicting requirements of adequate isolation and low cost. Oliva and Catravas [6] descibed a method for simultaneously exposing 10 animals in a conventional anechoic chamber with minimal field interaction between animals. The animals' cages are located on the antenna beam's three-dimensional contour of constant power density with cages separated by ~2.5 wavelengths at 2450 MHz. The authors claim that the average variation of power density from one cage location to another does not exceed ±5 percent. A major disadvantage of this technique is that its implementation requires a larger exposure volume. D'Andrea *et al.* [7], [8] developed an alternative method involving a monopole radiator on a vertical ground plane. The animals are located next to the ground plane on a circular locus that is centered at the monopole. Each circular array contains 10 animals that are separated by ~5.5 wavelengths at 2450 MHz and 2.1 wavelengths at 915 MHz. This system reduces both space and RF-power requirements. Furthermore, the presence of a ground plane makes this system more representative of the real-life exposure situation for humans. On the other hand, the exposure characteristics may not be entirely comparable to a conventional anechoic chamber facility so that caution is needed when comparing data.

For situations involving the exposure of only one subject at greatly increased power density values, D'Andrea *et al.* [9] discussed a modification of this system in which a 45° corner reflector is placed behind the monopole. By placing the monopole at a critical 0.25 wavelength distance from the reflector corner point, it is possible to obtain a 20-fold enhancement in SAR relative to that obtained without the reflector.

B. Enclosed Systems

Enclosed exposure systems are those in which the EM fields are largely contained within a conducting structure. These include transmission-line systems and cavity systems. The principal advantages of enclosed systems are as follows:

1) By suitable monitoring of the incident, reflected, and transmitted power levels (where applicable) in the exposure system, more accurate SAR estimates can be made for the exposed subject than is possible in free-field facilities. The accuracy to which this can be done depends on the extent to which baseline power loss for the unloaded system is affected by the presence of the exposed subject.

2) The cost and space requirements of such a system are usually lower than for free-field methods, depending on the number of identical systems needed. Also, much smaller and less expensive power sources suffice to establish the same field intensities.

3) Better control over the whole-body-averaged SAR in the irradiated subject is possible.

The principal disadvantages are as follows:

1) With the exception of transverse electromagnetic (TEM) mode transmission lines, the fields are complex and not plane-wave equivalent, thereby making comparison with free-field data more difficult.

2) The exposure space available inside such systems is limited. Though the available space may be satisfactory for small animals such as rodents, it may not be adequate for a rabbit or a monkey. Thus the variety of species that can be employed in an existing facility of the enclosed type is restricted.

3) The field distribution within the exposure system is rarely as uniform as that found in a free-field facility. The field distribution can usually be well defined for single- or dominant-mode operation, but is undefined for multiple-mode operation.

Enclosed systems have been the preferred method of exposure for samples, specimens, *in vitro* preparations, etc., since these are small enough to easily fit inside them. Many experiments have been described, too numerous to survey here, in which different types of waveguide, TEM mode lines, and cavities were used to irradiate such preparations. In recent years, a number of enclosed-type systems have been specifically designed for whole-body irradiation of animals. To accurately define the field levels to which the animal is exposed, dominant-mode operation of these devices is preferred over multiple mode. This perference, however, puts an upper limit on the frequency of operation, depending on the size of the system needed to expose the experimental animal of choice. For example, most of the dominant-mode enclosed systems that are used for exposing rats operate at frequencies below 1000 MHz; for mice, which require a smaller exposure volume, single-mode operation up to ~3000 MHz is possible. Since free-field exposure methods are impractical in the HF and VHF segments of the spectrum, as discussed earlier, enclosed systems do provide experimenters with virtually the only practical and economical method of exposing animals at such frequencies. A few large-scale systems were built to operate in the dominant mode at HF and lower VHF frequencies [10], [11]. These are large enough to accommodate a group of animals within the exposure area, and the animal-to-animal interaction problem is largely minimized because exposures are conducted in the subresonant region where interanimal scatter is minimal. However, at higher frequencies, these methods

become impractical and it becomes necessary to provide an identical exposure system for each animal to be irradiated. Each exposure device is fed from a single high-power source by a power-dividing network. One of the basic electrical problems associated with any enclosed exposure system is that when loaded with an animal in place, there is considerable reflection of RF energy from the load that propagates via the feed lines back to the RF power source. This situation creates particular problems for multiple systems fed from a single source because, without sufficient isolation between each exposure device, energy is continuously reflected from one system into the others, causing unwanted fluctuations in the incident power to each system. These problems can be solved by installing RF isolators in each feed line, thereby preventing the reflected energy from reaching the dividing network and the RF power source.

Another problem associated with exposures conducted within enclosed-type systems is that the exposed subject may alter the electric currents flowing in the walls of the system. Two undesirable consequences result: a) the magnitude and distribution of the fields within the enclosed system change, thereby creating uncertainty in the field strength or power-density levels to which the subject is exposed, and b) the baseline power loss of the empty or unloaded system also changes, thereby causing uncertainty in the SAR estimates obtained from monitoring the incident, reflected, and transmitted power levels.

The occurrence of interaction problems depends on the same factors as the extent of the subject's RF-energy absorption and its proximity to the walls of the system. Hill [12] performed measurements to determine the degree of interaction for a subject exposed under subresonant conditions in a TEM-mode transmission line and concluded that the interaction was negligible. However, the interaction effect is probably more pronounced when the frequency of operation lies in the resonant and superresonant absorption region of the exposed subject. Crawford [13] suggests a general rule whereby the exposed subject should not occupy more than one-third of the exposure system's cross-sectional area, thereby ensuring that interaction problems are no longer significant. However, this rule was developed for electronic equipment undergoing susceptibility testing and not for biological objects undergoing irradiation. It therefore appears prudent to verify SAR data obtained from power meter measurements using some form of calorimetry. These problems also emphasize the need to use whole-body-averaged SAR as the independent variable in RF biological effects studies rather than incident field strength or power density, particularly where enclosed-type exposure systems are used.

1) Transmission Lines: In these systems, an EM wave propagates down the line from source to termination. When the line is terminated in its characteristic impedance, only the outwardly propagating wave exists with no reflected wave present. However, if the line is terminated in a short circuit, or an open circuit all the energy is then reflected at the line's termination. The two systems of traveling waves create a standing-wave system that possesses successive maxima of E- and magnetic (H)-fields spaced 0.25 wavelength apart. This is a useful feature that is sometimes used to expose specimens or samples to E- or H-fields only, depending on their location along the line. A shorted or open transmission line has characteristics that are somewhat similar to those of the resonant cavity (see Section II-B2, Cavities).

Transmission-line devices can be subcategorized into TEM mode or waveguide. In TEM-mode lines, which include coaxial air lines, parallel-plate (strip) lines, etc., the dominant mode of operation is a propagating TEM mode provided the line is properly terminated in its characteristic impedance. In TEM-mode operation, the E- and H-field vectors are mutually orthogonal and lie only in the plane that is transverse to the direction of wave propagation. This arrangement is virtually identical to a plane wave, so that it is possible to simulate free-space conditions inside such lines. Because of its circular cross section, coaxial air lines are used only with fluid or precut solid samples; the primary application is usually for dielectric measurements. Guy [14] described a sophisticated coaxial air-line system designed to expose cell cultures to high field strengths. Parallel-plate systems, which consist of two or more parallel conductive plates, are better suited to animal exposures since they provide a rectangularly shaped volume where animals can be exposed. Capacitive plate devices, which are equivalent to a short length of parallel-plate line that terminates in an open circuit, are often used to expose *in vitro* preparations to E-fields only. This simple device was incorporated in a unique HF-band (10–40-MHz) exposure system developed by the National Bureau of Standards [15]. Termed a "near-field synthesizer," it is capable of separate E- and H-field excitation, the latter generated by special loop inductors. By altering the spatial position of the loop with respect to the E-field and changing the phase relationship between the signals exciting the plates and loop, it is possible to simulate the complex field environment existing in the near-field of an HF source.

Strip lines, in which a conductive plate is mounted either over a ground plane or between two ground planes, continue to be used by a few workers. Large-scale versions of a microstrip line with air dielectric that consist of a conductor-over-ground plane were described by Gandhi [16] and D'Andrea *et al.* [17]. The so-called "triple-plate lines," in which a conductor is mounted between two ground planes, allow for simultaneous irradiation of two animals while maintaining adequate isolation between them. Since there is better shielding, there is also less RF leakage than for the microstrip line. In a more popular version, the open sides of the structure are closed off with two side plates so that the center conductor is entirely surrounded by a rectangular ground structure [13]. Although various names have been used for this structure, the term "rectangular strip line" is preferred by these authors. These devices are commercially available in several different sizes from three suppliers: Instruments for Industry, Inc., Farmingdale, NY; Narda Microwave Corporation, Plainview, NY; and Amplifier Research Company, Souderton, PA. A major disadvantage of the closed strip-line structure relative to the open one is that higher order modes may propagate in the closed structure at much lower frequencies, given the same conductor-to-ground plane spacing [18], [19]. This means that the open-sided line possesses an inherently larger TEM-mode bandwidth.

Waveguides cannot support the propagation of a TEM mode so that the incident radiation is more complex than that of a plane wave; this creates differences in localized and whole-body-averaged SAR values due to significant alterations of the wave impedance from its free-space value. However, the lack

of a center conductor means that there is more exposure space available in waveguides than in the corresponding TEM line. Ho *et al.* [20] described a single, environmentally controlled system having a standard *S*-band rectangular waveguide for use in various studies on mice at 2450 MHz. Multiple systems using commercial waveguides are not used much for whole-body animal irradiation owing to high cost. Ho *et al.* [21] described a system of six waveguides fed from a common 2450-MHz source for simultaneous irradiation of six mice. Another problem is the high mismatch condition created by the animal's presence in the waveguide, which necessitates using isolation circuitry. This problem is partially eliminated in a specialized waveguide system developed by Guy and Chou [22]. Their system is specifically tailored for chronic whole-body irradiation of rats for extended periods of time with known and reproducible dosimetry. It consists of 20-cm (8-in) diameter circular waveguides economically constructed from galvanized wire mesh and short lengths of brass tubing, in which a circularly polarized TE_{11} dominant mode is excited at 915 MHz. Lebovitz and Nicoles [23] recently described a similar system of 15-cm (6-in) diameter waveguides capable of operation at 1300 MHz.

Circular polarization has two major advantages:

1) The wide variations in absorption due to constant changes in the animal's orientation and posture are largely eliminated so that the energy coupled to the animal load remains relatively constant. Whereas in a linearly polarized free field of perfect field uniformity the average SAR can vary by as much as ±5–8 dB at or near resonance, in this system the average variation of SAR does not exceed ±0.4 dB (±8 percent), even though the uniformity of the incident field is far from constant.

2) The hybrid coupler used to establish circular polarization in the waveguide provides a way to isolate the reflected from the incident energy emanating from the power source. This is done by dumping most of the unwanted reflected energy into a load connected to the hybrid rather than allowing it to return through the power-dividing network to the source. This technique effectively reduces the mismatch normally encountered with loaded waveguides (mean VSWR of $<1.5:1$) and reduces the isolation requirements in the feed network during parallel operation of multiple units.

Guy *et al.* [24] also described a modification of this waveguide system that operates in a multimoded field configuration at 2450 MHz. Although the complexity of the fields makes it difficult to define quantitatively incident energy levels in these units, absorption characteristics were well defined for rats of varying weights. An extensive system of 100 of these units is being used at the University of Washington [25] to conduct a chronic-irradiation study in which rats are continuously irradiated over a three-year life span. This feature underlines a major advantage of Guy's waveguide systems: animals can live in their exposure system with minimal disturbance to their normal living patterns and without artifactual perturbations for the duration of the study. Consequently, the system is ideal for the kind of chronic, long-term studies that are now being emphasized.

Another system specifically designed for such studies is being developed at the Georgia Institute of Technology [26]. It consists of a multiple stack of circular parallel-plate waveguides that are excited in the TE_{01} mode by a slotted-cylinder UHF antenna located at the center of the stack. The animals are arrayed around the circumference of each set of circular plates [diameter 3.7 m (12 ft)]. Though there exists little RF isolation between animals, this system is considerably less costly to construct than a multiple-waveguide system.

2) Cavities: The resonant cavity, which is the microwave analog of the RF-tuned circuit, consists basically of a cylindrical, rectangular, or square box with conductive walls. A system of standing waves may be excited within the cavity by small monopole or loop probes. By suitable adjustment of the cavity dimensions, the system can be made to resonate at the frequency of excitation such that intense field levels are created within the cavity using an RF source of relatively modest output.

A cavity system, therefore, represents the most efficient way of coupling RF energy into a biological subject. However, as in a waveguide, the fields are complex and wave-impedance values also differ considerably from the free-space value. Furthermore, the irradiation in a cavity is no longer unipath but multipath, thereby creating significant differences in the magnitude and distribution of absorbed RF energy in an irradiated subject. For a resonant cavity that is empty (unloaded) or that contains a biological load small in comparison to the cavity's volume (minimal loading), the fields in the cavity are only static and do not propagate. As such, the energy within is only stored. When the loading is greater (i.e., when the exposed subject occupies an appreciable fraction of the cavity's volume) the fields are hybrid and contain both stored and propagating energy. Because the fields are static, minimally loaded cavities are useful for simulating a quasi-static interaction in which object size is small relative to wavelength (i.e., a long-wavelength-type exposure). Furthermore, by simultaneously exciting more than one mode it is possible to control the wave impedance value at any specific location within the cavity, thus providing a capability of simulating exposures that take place in the near (reactive) field of a radiating antenna. Both these features were used by Guy *et al.* [27] who designed a large rectangular cavity that could be excited either separately or together in the TM_{110} or TE_{102} modes at frequencies of ~147 MHz. This system was used to study heating distributions in scaled-down phantom models of man separately exposed to E- or H-fields only, depending on the mode of excitation. Recently, Spiegel *et al.* [28] described an interesting variable-volume cavity that contains movable walls such that the cavity can be tuned across a wide frequency range. This system is also capable of simultaneously exciting two independent cavity modes. Single-mode cavities were also used by Edwards and Ho [29] to expose a monkey head at 385 MHz. Guy and Korbel [30] discussed the dosimetric aspects of a rectangular cavity used to multiply expose rats at 500-MHz, and emphasized some of the problems associated with cavity exposure systems.

Multimodal cavities, such as microwave ovens, have frequently been used for experimental purposes, since they are readily available and inexpensive [31]. Where ovens are used, they are generally modified to achieve the experimenter's objectives. Multimodal cavities are often preferred over single-mode types because of the larger exposure volume and the generally held opinion that the internal field distribution, which is constantly altered by a mode stirrer, is more uniform. Actual measurements on the internal field distribution of multimodal cavities do not always support this claim. Heynick, Polson, and Karp [32] described a multimodal cubical cavity suitable for irradiating nonhuman primates at 2.45 GHz where each unit

possesses its own regulated power source. Twelve of these units were constructed as part of an experiment involving chronic irradiation of squirrel monkeys.

C. Animal Holders

Experiments involving irradiation of nonanesthetized animals require the use of some form of holder or restrainer to keep the animal in a location of known field strength or power density. For a multiple-animal experiment, it is also necessary to keep animals separated from each other. From a dosimetric point of view, the optimal exposure condition is one in which the animal is totally constrained. The whole-body and regional dosimetry could then be determined with satisfactory precision. However, most biologists consider total constraint to be an excessive and unacceptable stress. Consequently, the accepted exposure environment is a compromise between these conflicting demands: the holder is designed to restrain the animal but still allows for a small degree of lateral and vertical movement.

An important criterion in designing animal holders is that they be constructed of materials that cause minimal perturbation to exposure fields. This means that cages can be built only from nonmetallic materials. Various types of low-loss dielectric materials that are available in rigid and semirigid form are the materials of choice. The most popular of these are the acrylic plastics (polymethyl methacrylate) because of their optical transparency and their superior mechanical strength and ease of machining. Several studies attempted to determine the degree to which these low-loss materials perturb incident fields [33], [34]. They showed that under certain conditions, the materials can indeed cause serious field perturbations implying that, in reality, the power density to which the animal is exposed in its restrainer is not known precisely. A possible solution is to use foamed polystyrene materials instead of acrylic. They have a relative permittivity value close to unity and, therefore, create minimal field perturbations. However, these materials have several disadvantages: they are optically opaque, so that animals cannot be observed, and they have little strength and can be readily gnawed by rodents. Coating the material with a substance to which rodents are averse, such as quinine, was used by a few workers [35], but this variation adds an additional insult on experimental subjects. Nonetheless, foamed polystyrene can be used for studies of short-term exposures.

A study by Ho [36] seems to question the significance of the incident field perturbations created by acrylic holders. Using a two-dimensional model containing a cylinder of muscle-equivalent material mounted concentrically inside an acrylic cylinder, Ho showed that despite the large perturbation of incident field existing in the empty holder, there is relatively little perturbation in the averaged SAR and SAR distribution inside the cylinder when compared with that which exists when no holder is present. Ho concluded that large field perturbations created by animal holders do not automatically create a correspondingly large perturbation in the animal's absorption rate because the presence of a mass of lossy dielectric (i.e., the animal) tends to damp out the standing-wave patterns created by the acrylic holder. These results appear to have been contradicted by some work of Gage *et al.* [37]. As part of a behavioral investigation, they investigated the influence of two different holders on the whole-body-averaged SAR for both rats and mice at 2450 MHz. One holder was a cubical container made of foamed polystyrene and the other an acrylic cylinder. They concluded that there was a significant alteration of SAR values for both species due to the acrylic cylinder when the animals were parallel to the E-field. This effect was considerably more pronounced in the mouse, probably because 2450 MHz is a frequency close to resonant absorption for the E-field parallel orientation of the mouse.

D. Feeding and Watering During Exposure

Experiments involving chronic, long-term irradiation of animals usually require some arrangements for food and water supply. Provision of food does not present any difficulties if standard dry food pellets are used since these absorb little RF energy. However, providing a supply of drinking water or liquid nutriment does present some problems because tap water, depending on ionic content, is a relatively good conductor and consequently, absorbs RF energy. Two basic methods of supplying water are used, and there are problems associated with each. In the first, the water reservoir is placed in the exposure system with the animal. The major disadvantage of this approach is that since the water supply is located in the same high-field-strength environment as the animal, it will both absorb RF energy and significantly perturb the surrounding fields. These factors create uncertainty in the dosimetry of the experiment. Caution is, therefore, advised; the reservoir should be kept as small as possible such that it contains no more water than that needed to meet the animal's average daily consumption.

The second method involves placing the reservoir outside the exposure system in a region of little or no field strength and supplying water to the animal via a supply tube or pipe. This method is superior, but it, too, has pitfalls which, without special precautions, can introduce serious experimental artifacts. As Guy and Chou [29] point out, the water tube or pipe provides a conductive pathway for microwave currents. When the animal attempts to drink, a closed circuit is created between the animal, which is at high potential, and the water reservoir, which is at zero or ground potential. This means that RF currents pass from the animal to the watering system. If the contact point is small and involves sensitive tissue, such as is the case when the animal attempts to drink, it is readily apparent that a high current density may exist in the animal's tongue. Since the animal is averse to this condition, it will probably refuse to drink. The solution is to find some way of interrupting the RF current flow through the water supply system. Guy devised two methods: a) the animal holder is equipped with a small water trough that is continuously supplied through a water drip system [5], and b) an RF choke assembly is placed between the animal and the water reservoir to decouple the drinking animal from the water supply [22]. In the choke assembly design, water is supplied through copper tubing, which forms the center conductor of a shorted quarter-wave section of a triaxial air line. To prevent the animal from coming into contact with the copper tubing, a short section of glass or acrylic tubing is mounted at its tip. The choke assembly effectively provides a high impedance at the point of animal contact, thereby reducing the RF current in the watering system to essentially zero.

III. Dosimetric Methods

This section covers techniques of dosimetric assessment of whole-body absorption and localized SAR, i.e., where and how much energy is absorbed by a biological subject. The method-

ology is divided into two areas: a) whole-body dosimetry, dealing with the integrated or spatially averaged SAR for the entire animal, and b) regional dosimetry, dealing with the localized SAR's or internal field strengths at a specific location in the animal.

A. Whole-Body Dosimetry

Whole-body dosimetry may be performed using either a Power Difference or a Calorimetric method. The Power Difference method is limited to closed exposure systems such as waveguides, TEM-mode transmission lines, cavities, etc. In this method, power meters are attached to the exposure systems by directional couplers to measure the incident, reflected, and transmitted power. The power absorbed by the biological target (whole-body absorption rate) is then measured by subtracting the values of the reflected and transmitted power from the incident power. For exposure systems using live animals, the values of these three measurements vary as the animals change position and posture because absorption is a function of the animal's orientation relative to the field polarizations. It is thus desirable to have a data collection system that can integrate the measured power difference and determine an average over a time period, usually for the duration of exposure [38], [39]. The advantage of this method is that it is capable of providing on-line instantaneous measurements of the whole-body absorption rate in live animals. As such, the method is useful for continuously monitoring absorption changes created by alterations in an animal's position, posture, etc., and can be used, for example, as a technique to remotely monitor an animal's breathing rate [40]. There are, however, some problems. In cases involving a multiple-animal exposure within the same closed system, the measured absorption rate represents the sum total for all animals. How this energy is apportioned among the animals within the system cannot be determined. The method is, however, optimal for single-animal exposures. Also, under long-wavelength interaction conditions where the whole-body absorption rate is low, the accuracy of obtained data may be unacceptable because measurement errors may exceed the computed power difference. Hill [12] discusses these problems extensively. As discussed earlier, some uncertainty remains in the SAR data derived from this method because of uncertainty in the amount of baseline loss in the unloaded exposure system.

Calorimetric methods employ the thermalization of absorbed power as a measure of SAR. Under the tacit assumption that all of the RF energy absorbed by a biological object is converted to heat, the calorimetric method measures the heat added to the object. The approach is to radiate an animal carcass with a short high-power exposure to reduce heat-loss errors due to conduction and convection during exposure. It is assumed that the dielectric properties of the carcasses are not significantly different from those of living animals, provided the measurements are made soon after death. The calorimeter measures the added heat in calories per unit time per unit mass, which is then converted to watts per kilogram and is the SAR obtained for the high incident power density used in the dosimetry experiment. The measured SAR can then be normalized to a 1-mW/cm^2 incident power density, where applicable. Three calorimetric methods have been used in whole-body dosimetry. The first uses the Gradient Layer Calorimeter, the second, the Dewar Calorimeter [41], [42], and the third, the Twin-Well Calorimeter [43], [44].

The Gradient Layer Calorimeter, also called a Seebeck Envelope Calorimeter, measures the rate at which heat passes from the heated animal through the walls of the calorimeter to the room air. It is accurate, but measurements require several hours to complete. These devices are commercially available in a wide range of sizes from the Thermonetics Corporation, San Diego, CA.

The Dewar Calorimeter measures the difference between the average temperature of the animal carcass before and after exposure to determine the heating rate, and thus the absorption rate. The average temperature is found by placing the carcass and coupling fluid, usually water, into a Dewar flask and measuring the equilibrium temperature of the mixture. From the theory of mixtures and the average specific heat capacity of the animal, the average carcass temperature is determined. The average temperature of the heated carcass can be similarly determined. Although simple, the method's drawbacks are the long measurement time required and the need to know the average specific heat capacity of the carcass, which, owing to the complex composition of the body, is not precisely known.

The Twin-Well Calorimeter method uses a pair of carcasses of equal mass. One carcass is heated using RF radiation, and both are then placed in the calorimeter, one in each well. The calorimeter is subsequently allowed to return to thermal equilibrium. The Twin-Well Calorimeter measures the increment of heat introduced by the exposure compared with the unexposed or reference carcass. The SAR is then calculated from the measured caloric increase, carcass mass, and exposure time. The major advantage here is that a knowledge of the specific heat capacity is not required. However, measurements can take from 4 to 16 h to complete. A recent improvement, which involves computerized control of the calorimeter, considerably reduces measurement times down to 30 min or less [45] and increases measurement accuracy. In this technique, a small heating element is placed in contact with the unexposed carcass located in the reference well. Using the Twin-Well Calorimeter as a "thermal" balance, a microprocessor controls the rate at which heat is applied to the reference carcass so that equilibrium is established as rapidly as possible. The energy applied to the heating element, and thus to the animal carcass, is integrated by the microprocessor to give the whole-body absorption, from which the average SAR can be derived.

B. Regional Dosimetry

Regional dosimetry assesses the localized internal field strength or SAR at a specific location within the target or the overall distribution of such throughout an internal region or cross-sectional slice of that target. The localized SAR is directly related to the RMS internal E-field strength E_t at that location by the following expression:

$$\text{SAR} = \frac{\sigma}{\rho} |E_t|^2 \text{ W/kg} \tag{1}$$

where σ is the tissue conductivity in siemens per meter and ρ is the tissue mass density in kilograms per cubic meter. Hence, one quantity is directly inferable from the other.

1) Internal Field Measurements: Direct measurement of internal E-field strength using miniature dipole probes implanted in the animal's tissues are superior to methods involving temperature-rise measurements since the former does not involve any tacit assumptions regarding total thermalization of the absorbed energy. Furthermore, localized SAR data in live animals can only be reliably derived using internal field probes since the animal's thermoregulatory mechanism will almost certainly create false readings when temperature-rise

methods are employed. Existing internal field probes have been developed by the Bureau of Radiological Health (BRH) [46], [47], among others. They are commercially available on special order from Narda Microwave Corporation, Plainview, NY. The BRH design consists of a miniature Schottky diode mounted between two dipole wing elements on a dielectric (epoxy–fiberglass) substrate. The detected signal is fed to a voltage readout device via a pair of high-resistance (0.1$M\ \Omega$/cm) thin-film leads that ensure that the probe leads are essentially transparent to the RF field for frequencies $\geqslant$300 MHz. In cases where the readout device needs to be remotely located from the probe, an optical telemetry system is available to transmit the detected signal data to the remote readout.

To date, the implantable probes used for internal field measurements are only of the single-axis type, whereas all three field components are needed to properly define the internal E-field strength. Although three-axis-type probes are available to measure external field levels, their diameters are too large to implant in animal tissues. The internal fields can be completely defined with a single-axis probe by taking three separate readings corresponding to a probe rotation of 0°, 120°, and 240°. The unknown field (E_t) is then proportional to the sum of the squares of the three detected voltage components (V_x, V_y, V_z), as expressed below

$$k|E_t|^2 = |V_x|^2 + |V_y|^2 + |V_z|^2 \tag{2}$$

where k is a proportionality constant.

The useful frequency range over which the BRH design operates is ~300–12 000 MHz. Below 300 MHz, the dipole elements become too small relative to the long wavelength with consequent loss of any usable detected signal. Also, RF pickup on the high-resistance leads becomes excessive. At frequencies above ~12 000 MHz, penetration of RF energy into tissues is so poor that it is no longer feasible to make internal field measurements.

An important requirement of any implantable field probe is that its response be relatively independent of the dielectric parameters of the biological medium in which it is immersed. As such, the probe would not require recalibration for every different type of tissue in which measurements are made, and can be used in complex regions containing dielectric inhomogeneities and boundaries. Cheung [48] and Smith [49] showed that a small dipole element insulated with a layer of low-loss dielectric material fulfills these requirements. In the BRH design, the probe is suitably insulated by epoxy encapsulation.

2) Temperature-Rise Measurements: Techniques to estimate localized SAR by measuring the rate of temperature increase or decrease continue to be widely used. Although these methods are relatively simple and often do not require sophisticated instrumentation, they are subject to the disadvantages discussed in the previous section. It must be emphasized again that using such methods to estimate the SAR in live animals is inapplicable and not recommended. Various workers discuss the use of heating and cooling curves to estimate localized SAR in *in vitro* samples, phantoms, etc. The most accurate of these methods appears to be that developed by Allis *et al.* [50]. If the rate of temperature rise is rapid and can be assumed to be linear, then a reasonably accurate approximation for the SAR is given by the following expression:

$$\text{SAR} = 4.186\,\frac{c\Delta T}{\Delta t}\ \text{W/kg} \tag{3}$$

where c is the tissue-specific heat in cal/g/°C, ΔT is the temperature increase in degrees centigrade, and Δt is the irradiation time in seconds.

The measurement of RF-induced temperature changes involves problems not normally associated with biological temperature measurements. When standard forms of thermocouple or thermistor element temperature probes are used, the presence of an RF field will likely create artifact responses in the probe due to both RF pickup on the probe leads and field perturbations caused by the conductive probe. McRee *et al.* [51] showed that thermocouple elements appear to be more susceptible than thermistor elements to such problems and that use of shielded leads, oriented normal to the RF-field polarization, further mitigates artifact problems. The easiest solution, one used by many investigators, is to switch off the RF field before introducing any temperature probes so that only the cooling curve is monitored. The obvious disadvantage of this technique is that only half the available heating-and-cooling data is used. Furthermore, there are many other applications besides local SAR estimation, such as, for example, the monitoring of animal rectal temperatures during RF-radiation exposure, which creates a critical need for methods of making artifact-free temperature measurements during exposures.

A number of so-called nonperturbing temperature probes were developed to respond to this need. The first uses the temperature-dependent changes in the optical reflectance properties of cholesteric liquid crystals [52]. Fiber-optic bundles transmit narrow-band red light from both an LED source to the liquid-crystal material located at the probe tip and subsequently transmit the reflected light back to a readout unit. This type of probe appears to have been supplanted by another design based on a standard thermistor element fed by high-impedance leads [53]. This design appears to be free of the operational problems that afflict the liquid-crystal unit, i.e., nonlinear response, instability, need for frequent recalibration, etc. The thermistor-based design is commercially marketed by Vitek, Inc., Boulder, CO. Several other nonperturbing temperature probe designs have been developed, including one based on the birefringent optical properties of an $LiTaO_3$ crystal [54]. A recently announced commercial development utilizes a sophisticated technique involving temperature-dependent changes in the UV fluorescence spectra of rare-earth phosphors [55]. As with the liquid-crystal and birefringent crystal probes, the UV excitation energy and the optical emission spectra are transmitted to and from the tip using fiber optics.

Thermographic imaging is a powerful technique for determining the cross-sectional distribution of localized SAR. It is used to great advantage in a few laboratories that can justify the high capital investment needed to develop this type of dosimetric capability. The method uses a thermographic camera containing a mirror-scanning system and a liquid nitrogen-cooled infrared detector, together with a data-collection system (camera and magnetic tape) that is sometimes interfaced to a minicomputer [56]–[58]. Thermographic imaging is performed using either frozen animal carcasses or full-sized and scaled-down phantoms composed of simulated dielectric materials having RF electrical properties equivalent to those of the actual tissues [56], [59]. To provide mechanical support and thermal insulation, the phantom or carcass is embedded in some RF-transparent medium such as urethane foam. This assembly is subsequently cut into two parts along the desired plane of observation. The surface of the cut plane is covered with either a thin polyethylene plastic film or with polyester "silk" screen material; the latter has the advantage of

ensuring electrical contact between both parts [57]. A thermographic image is made of the bisected plane surface after the assembled specimen is allowed to equilibrate thermally to room temperature. The assembled specimen is then exposed to an intense RF field for a short time, ensuring that the rate of temperature increase is approximately linear so that the SAR can be computed directly from the temperature change (ΔT) using the simple relationship given above. Exposing the specimen for only a short time ensures that there is insufficient time for heat conduction and diffusion to take place. After exposure, the specimen is rapidly disassembled and a second thermographic image is taken of the bisected plane surface. SAR data are derived from the point-to-point temperature changes. These data can be either averaged over a specific area or, by computerized contour plotting routines, used to generate contour plots of constant SAR. The accuracy of the thermographic technique appears to be reasonably well established depending on the known thermal emissivity of the tissues and tissue-equivalent material being used, as well as the degree of thermal diffusion that is allowed to take place [60]. Methods are available to correct for the latter.

IV. Conclusions

The various techniques used for experimental exposure and dosimetric assessment in RF biological effects studies were reviewed. It should be evident to the reader that significant improvements have occurred during the past decade. Most of the new techniques succeeded in overcoming the deficiencies inherent in earlier methodologies or in developing solutions where none existed. Continuing efforts are needed for further development. There also exists a critical need to sponsor the ready availability of equipment and instrumentation associated with existing and future experimental techniques from commercial sources. Such sponsorship helps ensure the rapid dissemination of the latest engineering developments throughout the RF biological effects research community, and undoubtedly contributes to marked improvements in the quality of research.

There are diverse exposure techniques, most of which differ considerably in field characteristics. Since each has its own advantages and disadvantages, the choice of which to use depends largely on the specific application and should be made in concert with the biologists during the preparation of experimental protocols. For experiments involving whole-body irradiation of animals, there is a need for some kind of standardized method of exposure on which most researchers can agree. Though such ideas have been proposed and discussed in the past, they remain controversial due to the difficulties of implementation. Many exposure requirements are conflicting, and, therefore, no one system can satisfy all the various experimental requirements. However, some agreement on standardization should enable experiments to be more readily replicated and effects more readily confirmed.

Further development of exposure systems specifically designed for chronic-irradiation studies with large animal populations is needed. The aim of such an effort is to emphasize economy without significantly sacrificing performance. There is also a need to verify the accuracy of whole-body SAR estimates obtained using the Power Difference method in enclosed exposure systems.

There is also a serious need to study comparison of absorption distribution and biological end points in a given animal using different forms of exposure. This particular problem can be summarized as follows: for the same experiment performed in different exposure systems involving plane-wave, complex, or multipath fields, are there differences in biological outcomes even where the same whole-body-averaged SAR is maintained throughout?

There also appears to be considerable scope for further improvements in dosimetric techniques. As the sophistication of research into RF-induced biological effects improves, and as the sites for many of the reported effects, particularly those associated with the nervous system, become better isolated and defined, there will be an ever-increasing need for localized dosimetry of greatly improved spatial resolution. This growth requires the continuing development of smaller field and temperature probes without significant loss of sensitivity and accuracy. There is a serious need for a three-axis *in situ* field probe, small enough to be readily implantable in animal tissue, yet strong and reliable enough to be used in everyday laboratory operations. (BRH is currently sponsoring such a development effort.) Further efforts are also needed to reduce the measurement times associated with calorimetry and to automate the process. In dosimetry studies involving phantoms, refinements are needed to improve the modeling of the actual inhomogeneous tissue structure of man and animals since most studies performed to date involve phantoms composed of only a single homogeneous tissue-equivalent material.

References

[1] E. J. Lerner, "RF radiation-biological effects," *IEEE Spectrum*, vol. 17, no. 12, pp. 51–59, 1980.

[2] C. H. Durney, M. F. Iskander, H. Massoudi, S. S. Allen, and J. C. Mitchell, *Radiofrequency Radiation Dosimetry Handbook* (2nd and 3rd eds.). Reports SAM-TR-78-22 and SAM-TR-80-22; USAF School of Aerospace Medicine, Brooks AFB, Texas, 78235, 1978 and 1980. See also: "Electromagnetic dosimetry for models of humans and animal: A review of theoretical and numerical techniques," *Proc. IEEE*, vol. 68, pp. 33–40, 1980.

[3] J. A. Elder and J. S. Ali, "The effect of microwaves (2450 MHz) on isolated rat liver mitochondria," *Ann. N.Y. Acad. Sci.*, vol. 247, pp. 251–262, 1975.

[4] H. H. Bassett, H. A. Ecker, R. C. Johnson, and A. P. Shepphard, "New techniques for implementing microwave biological exposure systems," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-19, no. 2, pp. 197–204, 1971.

[5] A. W. Guy, "Miniature anechoic chamber for chronic exposure of small animals to plane-wave microwave fields," *J. Microwave Power*, vol. 14, no. 4, pp. 327–338, 1979.

[6] S. A. Oliva and G. N. Catravas, "A multiple-animal array for equal power density microwave irradiation," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-25, no. 5, pp. 433–436, 1977.

[7] J. A. D'Andrea, O. P. Gandhi, J. L. Lords, C. H. Durney, C. C. Johnson, and L. Astle, "Physiological and behavioral effects of chronic exposure to 2450-MHz microwaves," *J. Microwave Power*, vol. 14, pp. 351–362, 1979.

[8] J. A. D'Andrea, O. P. Gandhi, J. L. Lords, C. H. Durney, L. Astle, L. L. Stensaas, and A. A. Schoenberg, "Physiological and behavioral effects of prolonged exposure to 915 MHz," *J. Microwave Power*, vol. 15, no. 2, pp. 123–135, 1980.

[9] J. A. D'Andrea, O. P. Gandhi, and J. L. Lords, "Behavioral and thermal effects of microwave irradiation at resonant and nonresonant wavelengths," *Radio Sci.*, vol. 12, no. 6(S), pp. 251–256, 1977.

[10] J. S. Allen, W. O. Hurt, J. H. Krupp, J. A. Ratliff, C. H. Durney, and C. C. Johnson, "Measurement of radiofrequency power absorption in monkeys, monkey phantoms, and human phantoms exposed to 10–50 MHz fields," in *Biological Effects of Electromagnetic Waves*, vol. II, C. C. Johnson and M. L. Shore, Eds. Rockville, MD: HEW Publ. (FDA) 77-8011, 1976, pp. 83–95.

[11] R. J. Smialowicz, J. S. Ali, E. Berman, S. J. Bursian, J. B. Kinn, C. Liddle, L. W. Reiter, and C. M. Weil, "Chronic exposure of rats to 100 MHz (CW): Assessment of biological effects," *Rad. Res.*, vol. 86, no. 3, pp. 488–501, 1981.

[12] D. A. Hill, "Human whole-body radiofrequency absorption studies using a TEM-cell exposure system," *IEEE Trans. Micro-*

wave Theory Tech., vol. MTT-30, pp. 1847–1854, Nov. 1982.
[13] M. L. Crawford, "Generation of standard FM fields using TEM transmission cells," *IEEE Trans. Electromag. Compat.*, vol. EMC-16, no. 2, pp. 189–195, 1974.
[14] A. W. Guy, "A method for exposing cell cultures to EM fields under conditions of controlled temperatures and field strength," *Radio Sci.*, vol. 12, no. 6(S), pp. 87–96, 1977.
[15] F. M. Greene, "Development of an RF near-field exposure synthesizer (10 to 40 MHz)," HEW Publication (NIOSH) 76-160, U.S. Dept. of Health, Education and Welfare, Public Health Service, Cincinnati, OH, 1976.
[16] O. P. Gandhi, "Discussion paper: Strong dependence of whole animal absorption on polarization and frequency of radio-frequency energy," *Ann. N. Y. Acad. Sci.*, vol. 247, pp. 532–538, 1974.
[17] J. A. D'Andrea, O. P. Gandhi, and R. P. Kesner, "Behavioral effects of resonant electromagnetic power absorption in rats," in *Biological Effects of Electromagnetic Waves*, vol. I, C. C. Johnson and M. L. Shore, Eds. Rockville, MD: HEW Publ. (FDA) 77-8010, 1976, pp. 257–273.
[18] C. M. Weil, W. T. Joines, and J. B. Kinn, "Frequency range of large-scale TEM mode rectangular strip lines," *Microwave J.*, vol. 24, no. 11, pp. 93–100, 1981.
[19] D. A. Hill, "Bandwidth limitations of TEM cells due to resonances," accepted for publication in *J. Microwave Power*.
[20] H. S. Ho, E. I. Ginns, and C. L. Christman, "Environmentally controlled waveguide irradiation facility," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-21, pp. 838–840, 1973.
[21] H. S. Ho, M. R. Foster, and M. L. Swicord, "Microwave irradiation apparatus design and dosimetry," in *Biological Effects of Electromagnetic Waves*, vol. II, C. C. Johnson and M. L. Shore, Eds. Rockville, MD: HEW Publ. (FDA) 77-8011, 1976, pp. 423–434.
[22] A. W. Guy and C. K. Chou, "System for quantitative chronic exposure of a population of rodents to UHF fields," in *Biological Effects of Electromagnetic Waves*, vol. II, C. C. Johnson and M. L. Shore, Eds. Rockville, MD: HEW Publ. (FDA) 77-8011, 1976, pp. 389–407.
[23] R. M. Lebovitz and N. A. Nicholes, "Computer-based operant behavioral system for microwave bioeffects research," *IEEE Trans. Biomed. Eng.*, vol. BME-28, no. 7, pp. 536–543, 1981.
[24] A. W. Guy, J. Wallace, and J. A. McDougall, "Circularly polarized 2450 MHz waveguide system for chronic exposure of small animals to microwaves," *Radio Sci.*, vol. 14, no. 6(S), pp. 63–74, 1979.
[25] A. W. Guy, C. K. Chou, R. B. Johnson, and L. L. Kunz, "Study of long term, low-level RF exposure on rats: A plan," *Proc. IEEE*, vol. 68, no. 1, pp. 92–97, 1980.
[26] J. C. Toler, B. Jenkins, and J. Schaefer, "A new radiation facility concept for chronic exposure of large rodent populations," presented at 3rd Annu. Bioelectromagnetics Conf., Washington, DC, Aug. 1981. See Abstracts, p. 83.
[27] A. W. Guy, M. D. Webb, and C. C. Sorenson, "Determination of power absorption in man exposed to high frequency electromagnetic fields by thermographic measurements on scale models," *IEEE Trans. Biomed. Eng.*, vol. BME-23, no. 5, pp. 361–371, 1976.
[28] R. J. Spiegel, W. E. Oakey, and E. L. Bronaugh, "A variable-volume cavity electromagnetic near-field simulator," *IEEE Trans. Electromag. Compat.*, vol. EMC-22, no. 4, pp. 289–297, 1980.
[29] W. P. Edwards and H. S. Ho, "RF cavity irradiation dosimetry," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-23, no. 3, pp. 311–313, 1975.
[30] A. W. Guy and S. F. Korbel, "Dosimetry studies of UHF cavity exposure chamber for rodents," in *Summaries of Presented Papers for 1972 Microwave Power Symp.* (Ottawa, Ont., Canada, Int. Microwave Power Institute, Edmonton, Alta.), pp. 180–193, 1972.
[31] D. R. Justesen, D. M. Levinson, R. L. Clarker, and N. W. King, "A microwave oven for behavioral and biological research: Electrical and structural modifications, calorimetry, dosimetry, and functional evaluation," *J. Microwave Power*, vol. 6, pp. 237–258, 1971.
[32] L. N. Heynick, P. Polson, and A. Karp, "A microwave exposure system for primates," *Radio Sci.*, vol. 12, no. 6(S), pp. 103–110, 1977.
[33] C. M. Weil, "Propagation of plane waves through two parallel dielectric sheets," *IEEE Trans. Biomed. Eng.*, vol. BME-21, no. 2, pp. 105–108, 1974, Addendum and Corrections, vol. BME-24, no. 1, pp. 78–80, 1977.
[34] J. C. Lin, H. I. Bassen, and C. L. Wu, "Perturbation effect of animal restraining materials on microwave exposure," *IEEE Trans. Biomed. Eng.*, vol. BME-24, no. 1, pp. 80–83, 1977.
[35] G. N. Catravas, "Styrofoam cages for rats used in microwave research: Coating with quinine," *Health Phys.*, vol. 31, pp. 33–39, 1976.
[36] H. S. Ho, "Effects of plexiglass animal holders on microwave energy absorption," *IEEE Trans. Biomed. Eng.*, vol. BME-25, no. 5, pp. 474–476, 1978.
[37] M. I. Gage, E. Berman, and J. B. Kinn, "Video observation of rats and mice during an exposure to 2450 MHz microwave radiation," *Radio Sci.*, vol. 14, no. 6(S), pp. 227–232, 1979.
[38] C. L. Christman, H. S. Ho, and S. Yarrows, "A microwave dosimetry system for measured sampled integral-dose rate," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-22, no. 12, pp. 1267–1278, 1974.
[39] H. S. Ho and W. P. Edwards, "Oxygen-consumption rate of mice under differing dose rates of microwave radiation," *Radio Sci.*, vol. 12, no. 6(S), pp. 131–138, 1977.
[40] C. J. Gordon, "Measurement of breathing rate in unrestrained mice using microwave radiation," submitted to *IEEE Trans. Biomed. Eng.*, 1983.
[41] C. F. Blackman and J. A. Black, "Measurement of microwave radiation absorbed by biological systems, 2, Analysis of Dewar-flask calorimetry," *Radio Sci.*, vol. 12, no. 6(S), pp. 9–14, 1977.
[42] S. J. Allen and W. D. Hurt, "Calorimetric measurements of microwave energy absorption by mice after simultaneous exposure of 18 animals," *Radio Sci.*, vol. 14, no. 6(S), pp. 1–4, 1979.
[43] E. L. Hunt and R. D. Phillips, "Absolute physical dosimetry for whole animal experiments," in *Joint U.S. Army/Georgia Inst. Technol. Microwave Dosimetry Workshop, Dig. of Papers* (Washington, DC, Walter Reed Army Inst. of Res.), pp. 74–77, 1972.
[44] J. B. Kinn, "Whole-body dosimetry of microwave radiation in small animals: the effect of body mass and exposure geometry," *Radio Sci.*, vol. 12, no. 6(S), pp. 61–64, 1977.
[45] J. B. Kinn and G. E. Anderson, "A microprocessor controlled calorimeter," *Bioelectromagnetics*, vol. 1, no. 2, p. 239, 1980.
[46] H. Bassen, A. Herchenroeder, A. Cheung, and S. Neuder, "Evaluation of an implantable electric-field probe within finite simulated tissues," *Radio Sci.*, vol. 12, no. 6(S), pp. 15–25, 1977.
[47] H. Bassen, "Internal dosimetry and external microwave field measurement using miniature electric field probes," in *Biological Effects and Measurement of Radio Frequency/Microwaves*, H. Hazzard, Ed. Rockville, MD: HEW Publ. (FDA) 77-8026, 1977, pp. 136–151.
[48] A. Y. Cheung, "Electric field measurements within biological media," in *Biological Effects and Measurements of Radio Frequency/Microwaves*, H. Hazzard, Ed. Rockville, MD: HEW Publ. (FDA) 77-8026, 1977, pp. 117–135.
[49] G. Smith, "A comparison of electrically short bare and insulated probes for measuring the local radio frequency electric field in biological systems," *IEEE Trans. Biomed. Eng.*, vol. BME-22, no. 6, pp. 477–483, 1975.
[50] J. W. Allis, C. F. Blackman, M. L. Fromme, and S. G. Benane, "Measurement of microwave radiation absorbed by biological systems, 1, Analysis of heating and cooling data," *Radio Sci.*, vol. 12, no. 6(S), pp. 1–8, 1977.
[51] D. I. McRee and F. T. Pendergras, "Interaction of a 2450 MHz microwave field with thermocouples and thermistors," *Health Phys.*, vol. 25, pp. 180–182, 1973.
[52] T. C. Rozzel, C. C. Johnson, C. H. Durney, J. L. Lords, and R. G. Olsen, "A nonperturbing temperature sensor for measurements in electromagnetic fields," *J. Microwave Power*, vol. 9, no. 3, pp. 241–249, 1974.
[53] R. R. Bowman, "A probe for measuring temperature in radio-frequency-heated material," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-24, pp. 43–45, 1976.
[54] T. C. Cetas, "A birefringent crystal optical thermometer for measurements of electromagnetically induced heating," in *Biological Effects of Waves*, Vol II, C. C. Johnson and M. L. Shore, Eds. Rockville, MD: HEW Publ. (FDA) 77-8011, 1977, pp. 338–348.
[55] Luxtron, "Fluoroptic thermometry," Luxtron Corp., 1060 Terra Bella Ave., Mountain View, CA 94043, Tech. Note 80-1, 1981.
[56] A. W. Guy, "Analysis of electromagnetic fields induced in biological tissues by thermographic studies on equivalent phantom models," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-19, no. 2, pp. 205–214, 1971.
[57] A. W. Guy, M. D. Webb, and J. A. McDougall, "A new technique for measuring power deposition patterns in phantoms exposed to EM fields of arbitrary polarization—example, the microwave oven," in *Proc. Microwave Power Symp.* (Waterloo, Ont., Canada), pp. 36–47, 1975, published by Int. Microwave Power Inst., Edmonton, Alta., Canada.
[58] G. Kantor and T. C. Cetas, "A comparative heating pattern study of direct-contact applicators in microwave diathermy," *Radio Sci.*, vol. 12, no. 6(S), pp. 111–120, 1977.
[59] M. A. Stuchly and S. S. Stuchly, "Dielectric properties of biological substances—tabulated," *J. Microwave Power*, vol. 15, no. 1, pp. 19–26, 1980.
[60] T. C. Cetas and G. Kantor, "Infrared emittance of electromagnetic phantom materials and infrared transmittance of polyethylene," in *Biological Effects and Measurement of Radio Frequency/Microwaves*, H. Hazzard, Ed. Rockville, MD: HEW Publ. (FDA) 77-8026, 1977, pp. 152–169.